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Ultra-smooth $BaTiO_3$ surface morphology using chemical mechanical polishing technique for high-k metal-insulator-metal capacitors

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ABSTRACT

The surface roughness of barium titanate (BTO) following its implication by aerosol deposition method (ADM), is a very important characteristic affecting its potential for use in high-k metal-insulator-metal capacitors. The ADM is the best candidate to deposit ceramic films but has two major problems: macroscopic defects and rough interface effects on the BTO surface. In this work, a chemical mechanical polishing (CMP) technique is applied to obtain an ultra-smooth BTO surface morphology by the optimization of several factors including the slurry type, the head rotational speed, and the down pressure. Statistically, we were able to achieve a root mean square (RMS) value of the BTO surface of 1.746 nm by utilizing a two-step polishing process, applied at a head rotational speed of 70 rpm under 5 kg/cm^2 of down pressure; this RMS value is improved at least 8 times over previous studies. This analysis is based on representative pattern images, three-dimensional images, line profiles, histograms, and power spectra of selected BTO surface areas, further verified with data from both energy-dispersive X-ray spectroscopy and X-ray photoelectron spectroscopy.

1. Introduction

Metal-insulator-metal (MIM) capacitors offer potential for radio frequency (RF) and mixed-signal integrated circuit (IC) applications because they utilize highly conductive electrodes [1], demonstrate low parasitic capacitance [1], and are extremely reliable [2]. These capacitors are also compatible with semiconductor processes and are therefore an essential technology for system-in-package and system-on-chip developments, which are expected to be key next-generation system implementation approaches [3,4]. Conventionally, SiN_x (ε_r=7.5) and SiO_2 (ε_r=3.7) are used as dielectric materials in the design of MIM capacitors because of their good voltage linearity properties and low temperature coefficients [1]. Nevertheless, due to the low dielectric constants of SiN_x and SiO_2, capacitors using these materials have a limited capacitance density, and it is therefore practically impossible to use them as by-pass capacitors, direct current (DC)-block capacitors, or in super-capacitor-based applications, all of which demand high capacitance and high-k dielectrics [5,6].

Barium titanate (BTO), with an extremely high dielectric constant of approximately 300, low leakage current, and excellent piezoelectric and ferroelectric properties, is a promising solution to the low dielectric constant limitations of conventional SiN_x and SiO_2 dielectric materials [7,8]. Among several possible deposition processes, the aerosol deposition method (ADM) is the best candidate because it does not require a sintering process to deposit ceramic films and also because of its optical transparency, high strength, and strong adhesion with a high speed deposition rate [9,10]. However, the ADM process creates two major problems: macroscopic defects and rough interface effects; these reduce the breakdown voltage [11], increase the leakage current [11], and increase the risk of an electric shortage [12].

Different techniques have been studied and applied over the years to minimize the surface roughness of BTO. High-k dielectric materials cannot be chemically etched, and the plasma etching process is not efficient as it suffers from a low etching rate and generates poor sidewall angles [7]. Chemical mechanical polishing (CMP), which involves the planarization of the oxide surface by rotating the wafer under pressure against a polishing head in the presence of silica-based alkaline slurry, is one of the most effective techniques to prevent macroscopic defects and reduce BTO surface roughness [13]. Oxide polishing is performed chemically, mechanical energy is imparted to the abrasive slurry through pressure, and the planarization of the surface is achieved by rotation [14]. Seo et al. evaluated the CMP characteristics of BTO surfaces processed using a mixed abrasive slurry; however, they did not consider the effects of several decisive parameters, such as the down pressure and rotational speed [7]. Moreover, the data

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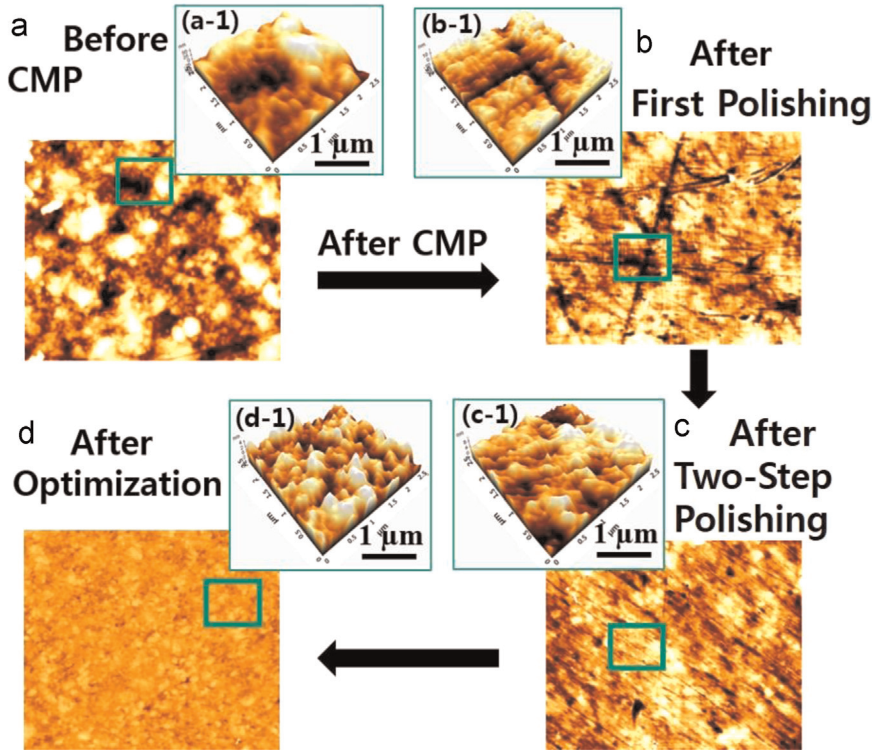

Fig. 1. BTO surface roughness (a) before CMP, without slurry, (b) after CMP, with one-step polishing, (c) after CMP, with two-step polishing, and (d) the optimized result obtained with two-step polishing at a rotational speed of 70 rpm under a down pressure of 5 kg/cm^2. Subfigures (a-1)–(d-1) show respective three-dimensional images of selected respective rectangular areas.

concerning the surface morphology properties of such polished films were not favorable when compared with SiN_x and SiO_2 films fabricated by plasma-enhanced chemical vapor deposition.

In this paper, the following CMP parameters are examined: slurry type, down pressure, and rotational speed. Each of the individual parameters was systematically analyzed, and the optimized result of one parameter was applied to the next parameter assessment. This new analytical and statistical approach will contribute significantly to the development of high dielectric BTO with improved surface smoothness. Fig. 1(a)–(c) shows surface morphologies of the BTO films before and after the implementation of the proposed polishing techniques, with magnified three-dimensional views of those areas indicated by the rectangles. The influences of changing the slurry type, rotational speed, and down pressure are clearly recognizable, and the optimized result of the aforementioned process is shown in Fig. 1(d).

2. Experiment

BTO thin films were deposited using an ADM and a commercial crystalline BTO powder (SBT-045J, Samsung Fine Chemicals Co., Ltd., Ulsan, South Korea) with an average particle size of 450 nm, a high density over 95% of bulk density, and a thickness of 2.5 μm [15]. The BTO particles were aerosolized in an aerosol head and transported into the deposition head using N_2 gas at a flow rate of 5 L/min. The transported particles were continuously ejected through a nozzle and deposited onto Pt/Ti/SiO_2/Si substrates. The nozzle orifice was 10 mm wide with a 0.4 mm slit width, the deposition area was 10×10 mm^2, the distance between the nozzle and substrates was 10 mm, the working pressure was 3.4 Torr, and the deposition time was 10 min. The details of the ADM apparatus can be reviewed in [16].

All of the test wafers used in these experiments were polished using a CMP technique (DS-Precision, DS Precision Industrial Co. Ltd.). Several parameters of the CMP process were fixed as follows: the slurry flow rate and the distance between the center of the table and the center of the head were 80 mL/min and 11.43 cm, respectively. Different samples were repeatedly tested by varying the parameters of slurry type, rotational speed, and down pressure, and the outcomes for each parameter were analyzed independently based on the root mean square (RMS) of the surface protrusions before proposing the final optimized outcome. Five points, from the top, bottom, left, right, and center parts of the sample, were measured for each polishing condition, and the final value for each polishing condition was the average value of these five measured points. The post-CMP cleaning proceeded as follows: 5 min in SC-1 (NH_4OH:H_2O_2:H_2O = 1:2:7), 3 min in diluted HF (1:10), and 7 min in ultrasonic cleaning. The surface morphologies of the as-deposited and polished BTO films were examined using atomic force microscopy (AFM) (XE-100, PSIA Co., South Korea). Finally, energy-dispersive X-ray spectroscopy (EDS) (S-4300SE, Hitachi Ltd., Japan) and X-ray photoelectron spectroscopy (XPS) (PHI 5000 VersaProbe^{TM}, ULVAC-PHI, Japan) were applied to analyze the chemical composition of the BTO samples before and after polishing. The schematic of the BTO CMP mechanism is shown in Fig. 2.

3. Results and discussion

3.1. Effect of slurry type

The effect of slurry type on the upper surface of the BTO films can be clearly observed from Fig. 3. Fig. 3(a) shows an image of the upper surface of a BTO film following the application of the ADM, which generated significant roughness on the surface. Subsequent rounds of polishing were performed with a head rotational speed